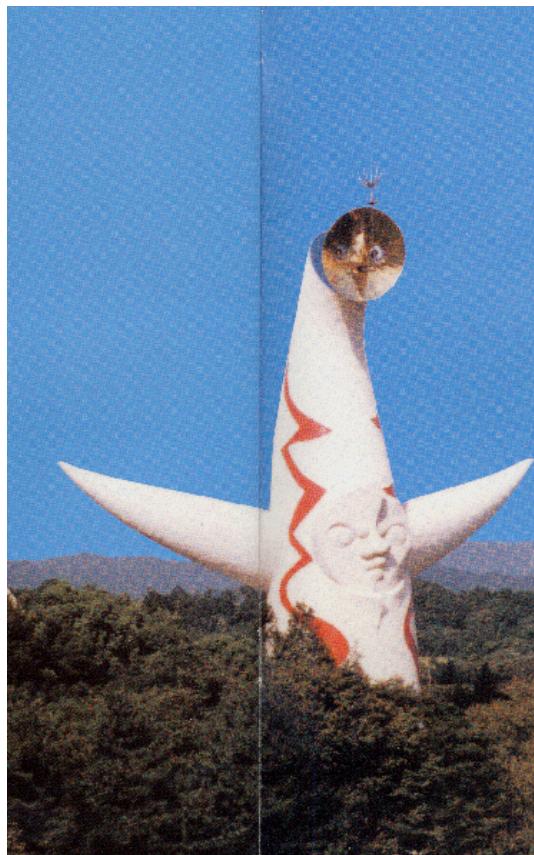


# High Repetition High Average Power Nd:YAG Laser System for EUV Lithography



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Hamamatsu Photonics



# What is EUV Laser ? Why at ILE ?

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## Requirements for EUV Laser

Output Energy	: 1 - 3 J/pulse → 2 - 6 J/cm <sup>2</sup>
Pulse Duration	: 1 - 10 ns
Repetition Rate	: 5 - 20 kHz
Stability	: ± 0.3 % (3σ, Ave. of 50 pulse)

## Concepts of ILE, Osaka Univ.

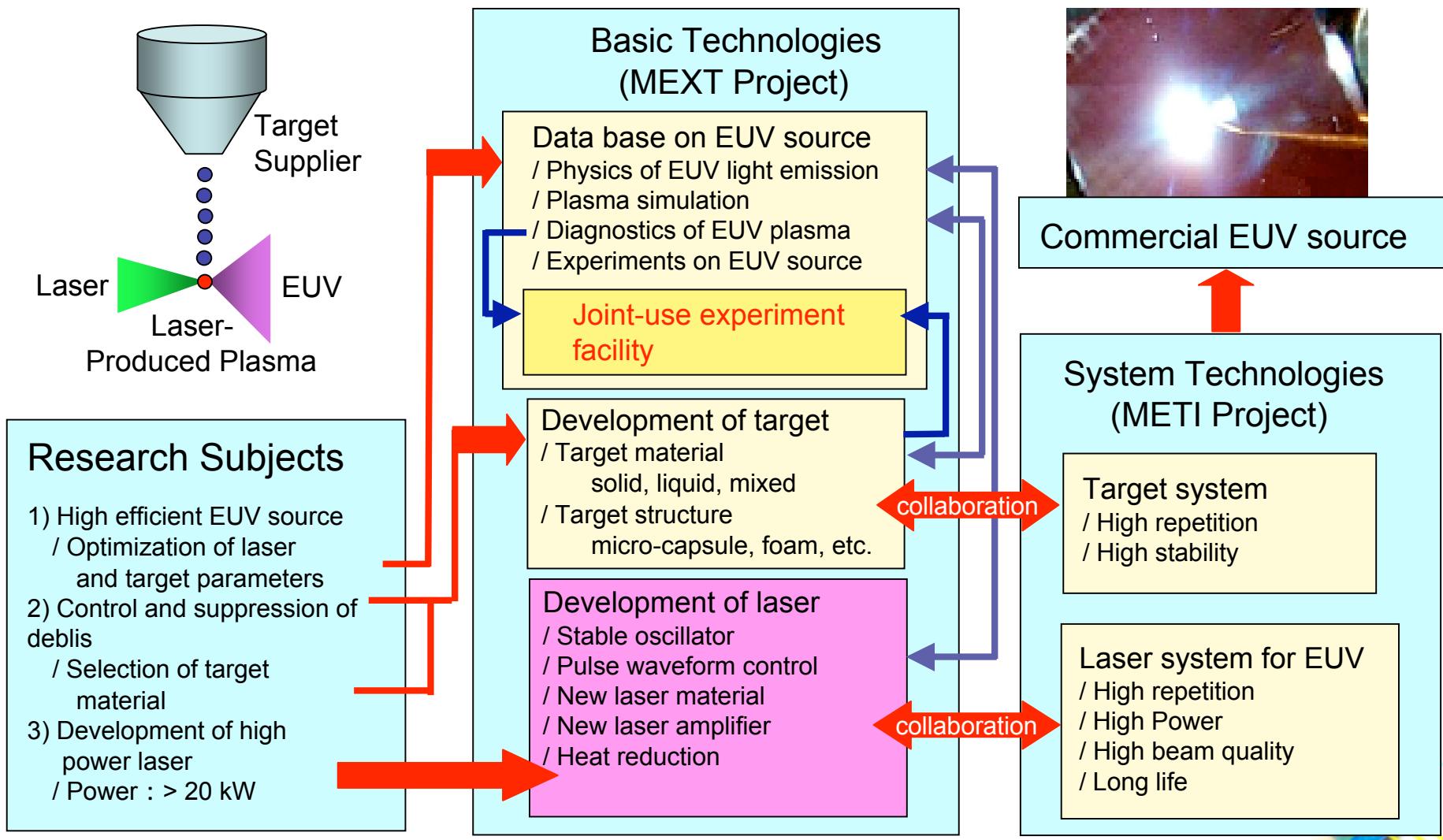
Oscillator	: Fiber Laser (Reliability & Stability)
Main Amplifier	: Rod (or Disk) Pumped by CW LDs Strong and Uniform Pumping → Thermal Fracture Limit, Thermal Effects
System	: Computer Control (Alignment, Compensation of Thermal Effects)

Future Driver for Laser Fusion

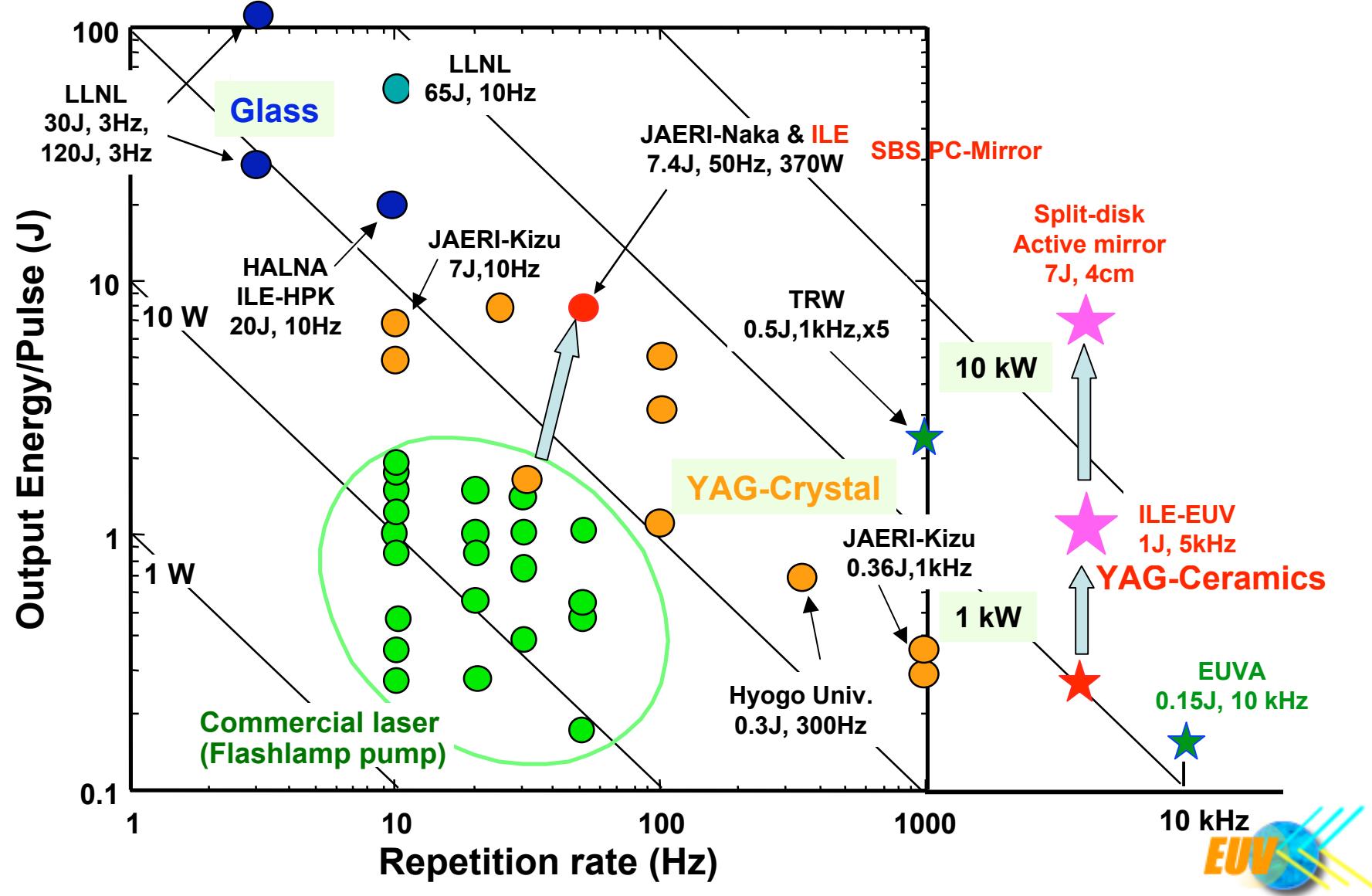


# Project on Extreme Ultra Violet Light Source Development

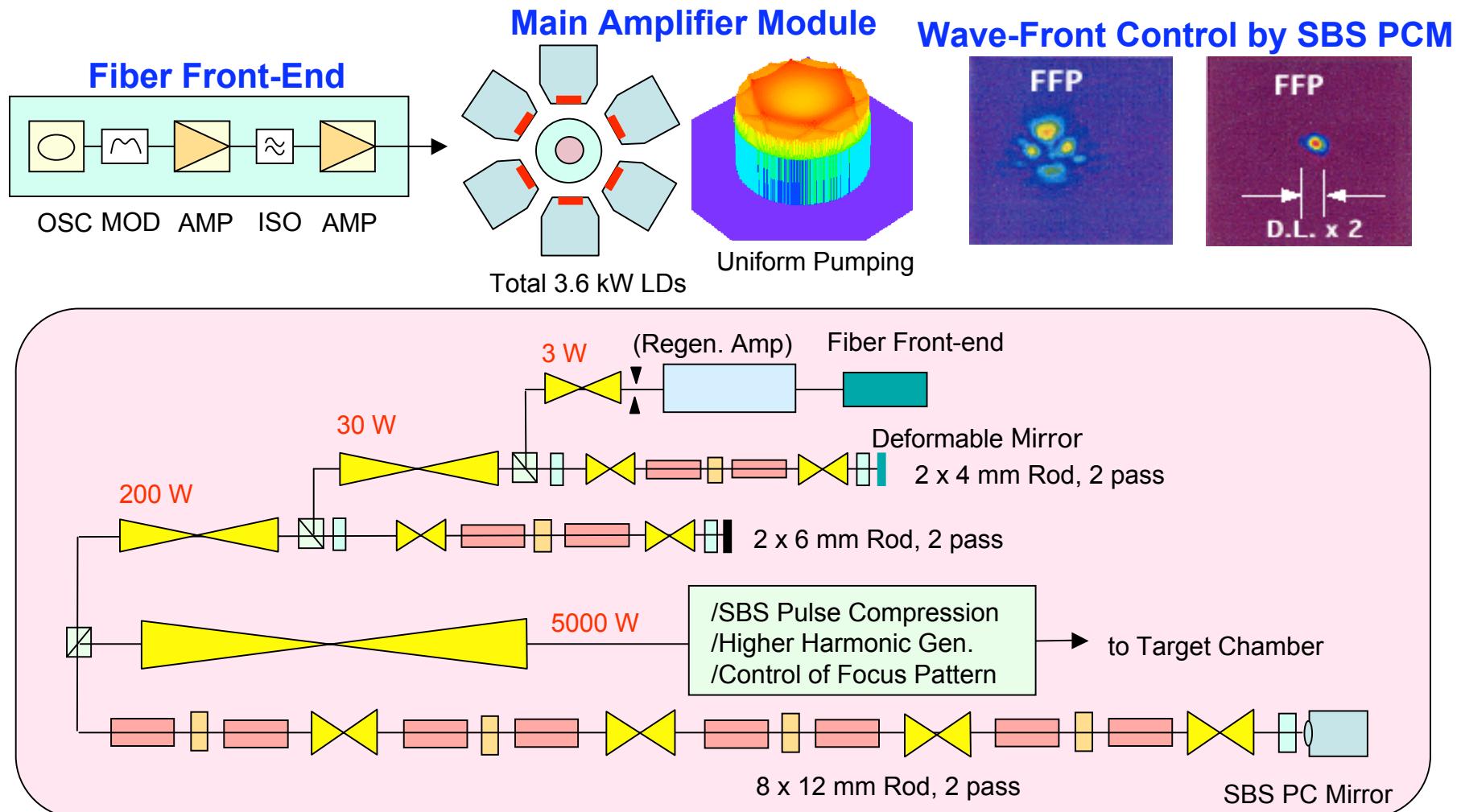
EUV light source and laser fusion research are standing on common scientific bases. ILE Osaka-U. has started EUV light source development.



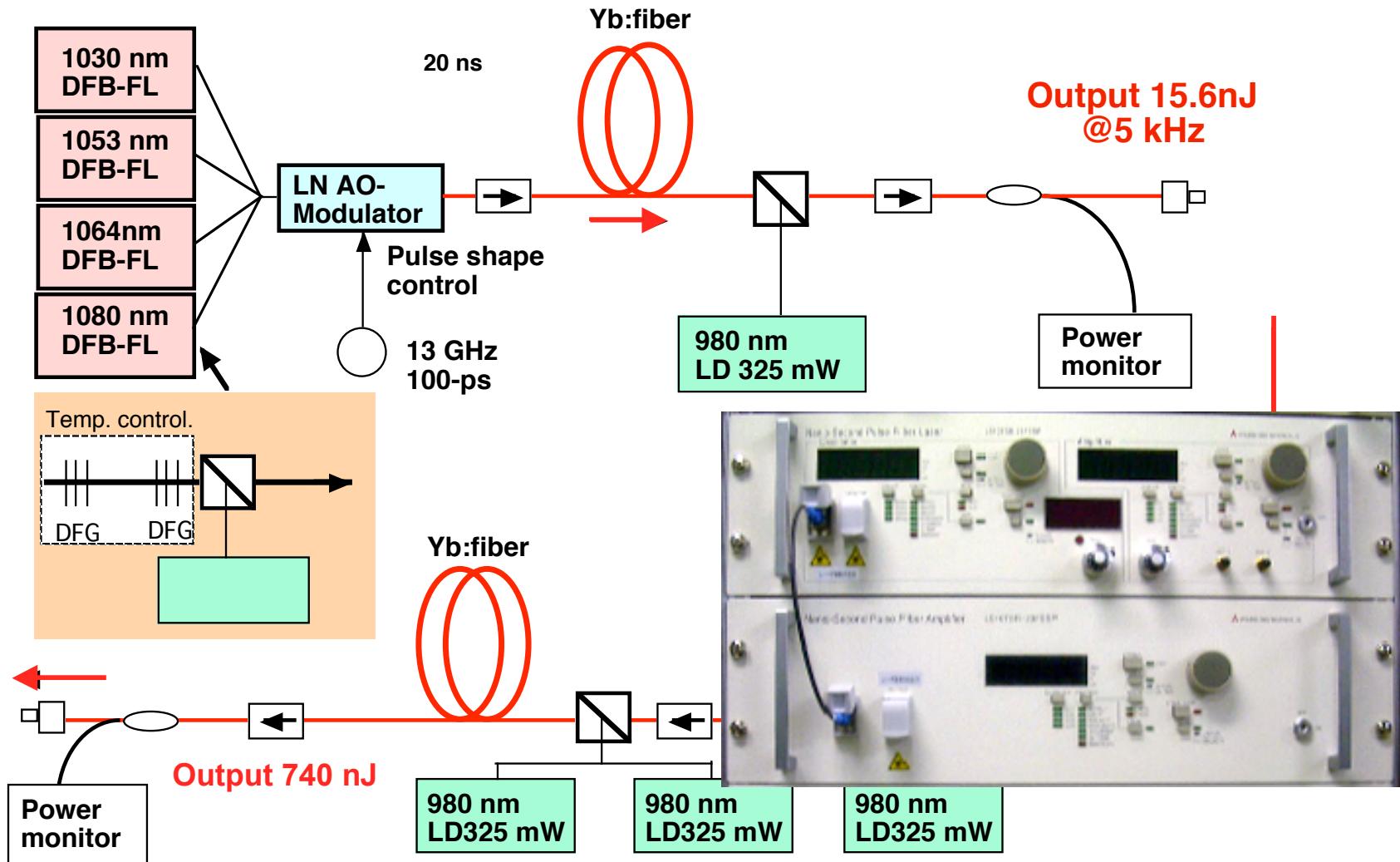
# High Average Power Pulse Laser in the World



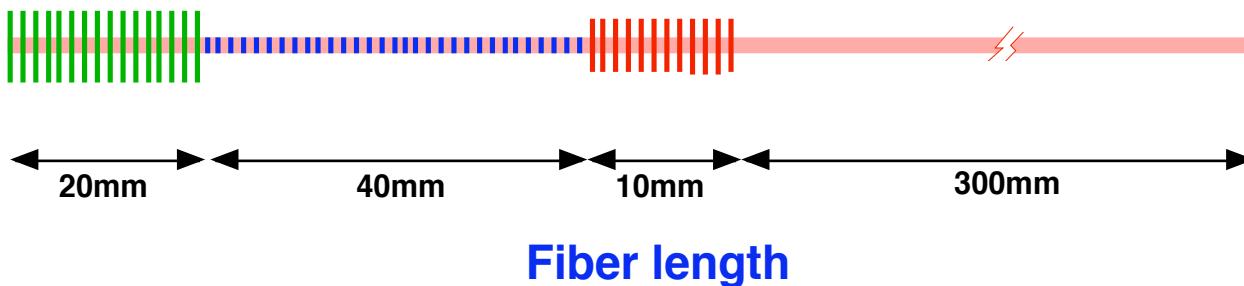
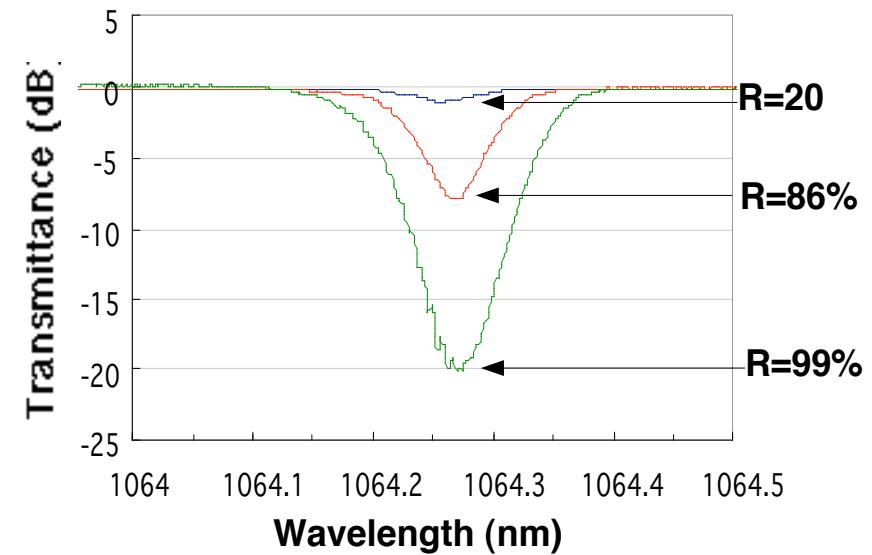
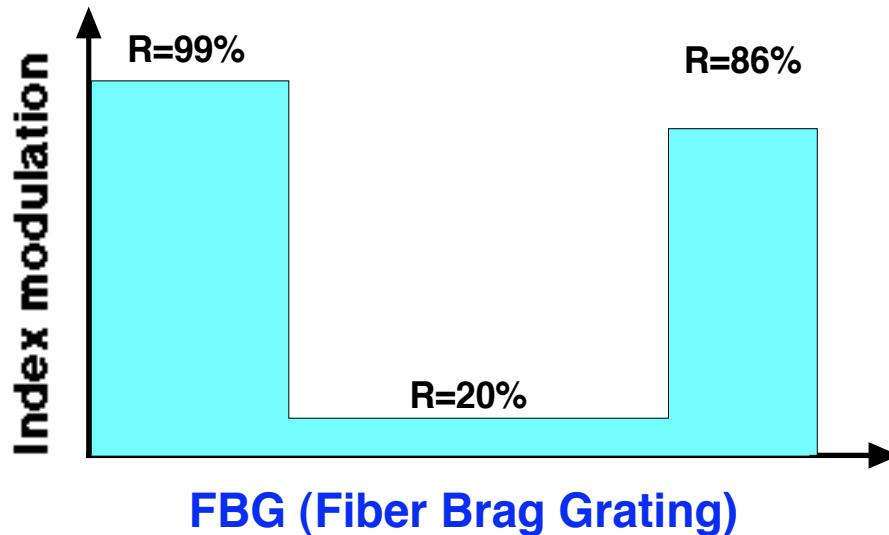
# 5 kW (1J / 5 kHz) Laser System for EUV Lithography



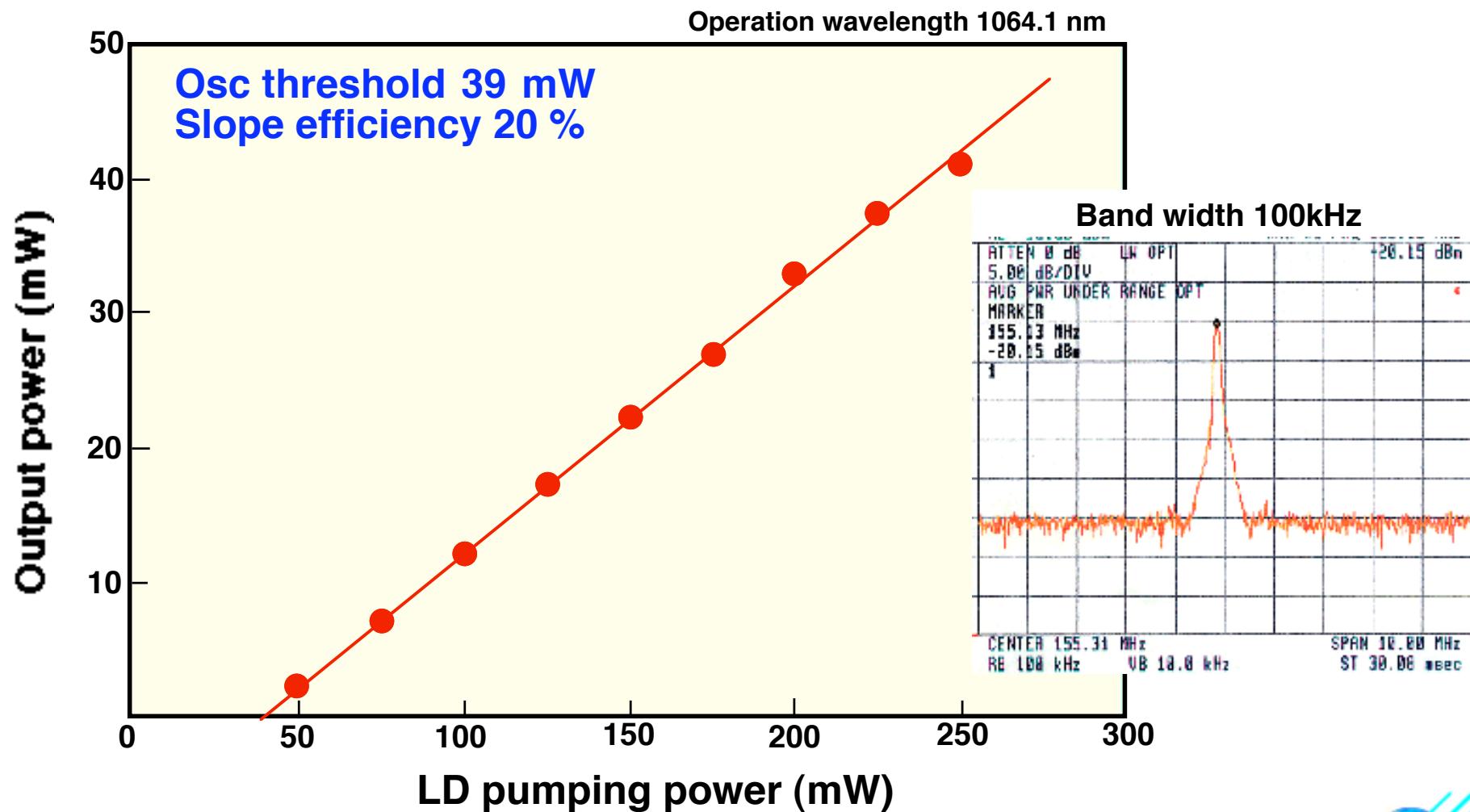
# Layout of Yb:fiber oscillator and amplifier system



# Single-longitudinal mode Yb-silica fiber oscillator by FBG



# CW output power as a function of pumping power



# Summary (Frontend)

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## Development of Yb:silica fiber master oscillator and amplifier system

Single longitudinal mode oscillation by FBG (fiber bragg garting)

Band width                    100kHz

Turning range                1030, 1053, 1064, 1080  $\pm 0.5$  nm

Extremely precise            0.1 pm

CW output power            40 mW (slope efficiency 20 %)

Switch out by EO modulator 1 - 3 ns

Pulse output energy        740 nJ, 3 ns (@5 kHz)

## Development of CW pumped Nd:YAG regenerative amplifier system

Output beam quality        TEM<sub>00</sub> mode,  $M^2=1.1$

Maximum output energy     1.12 mJ (@1 kHz),  $G= 3.7 \times 10^5$

Maximum output power     5.3 W (@5 kHz)

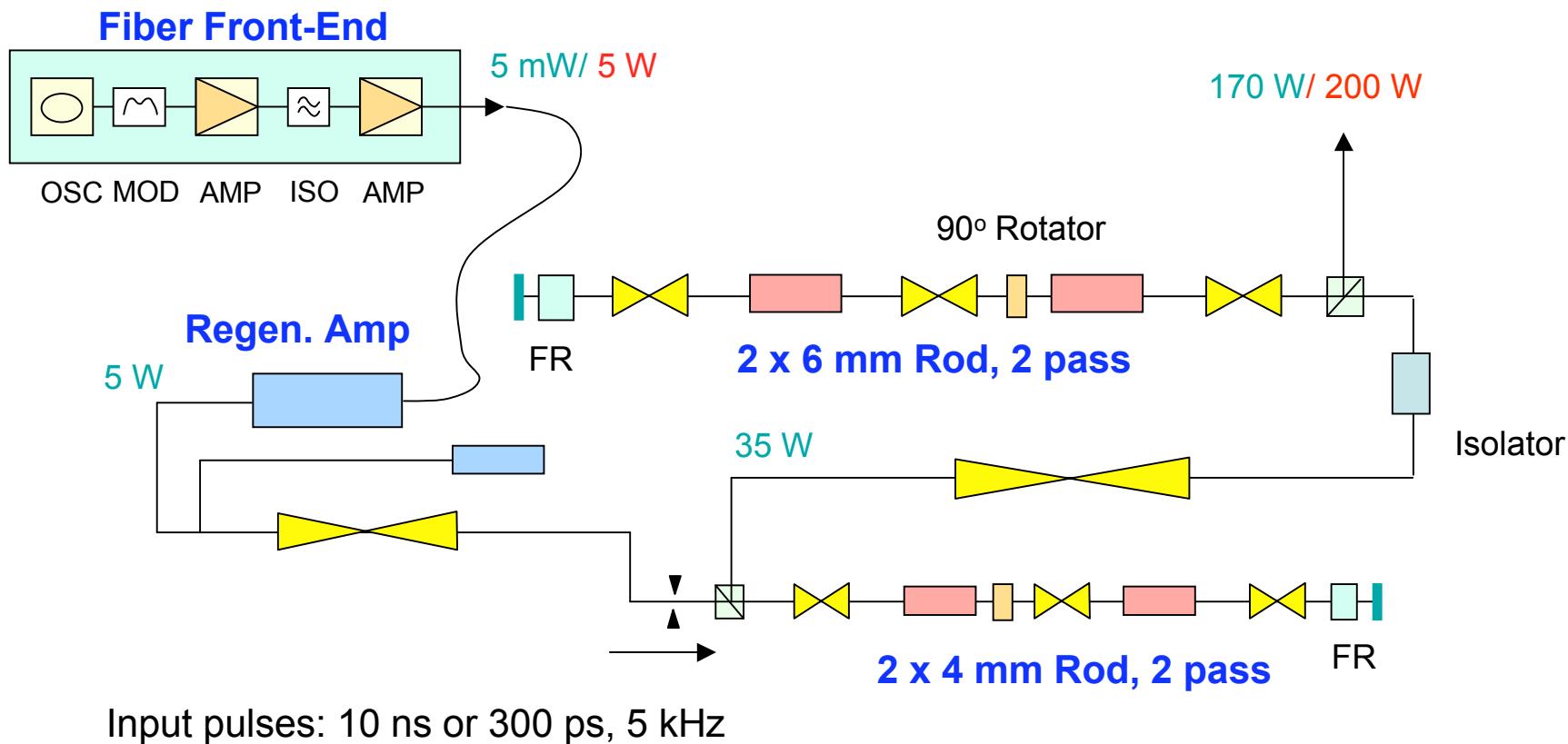
## (1) High-average-power Yb:fiber laser system

Output power 5W(@1mJ, 5kHz)

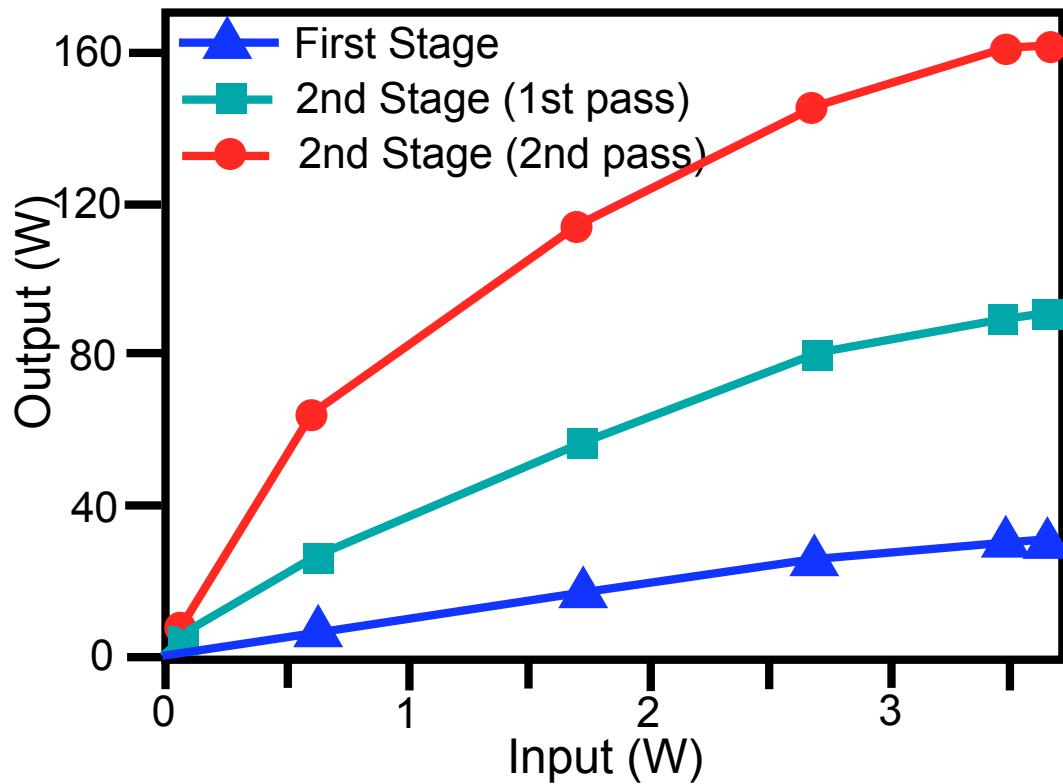
## (2) Arbitrary pulse shape control



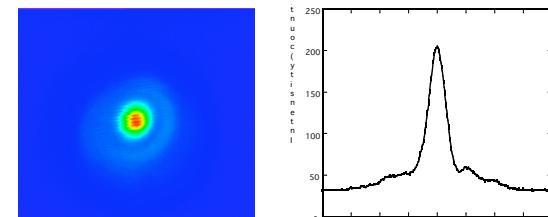
# Optical Layout of Pre-amplifiers



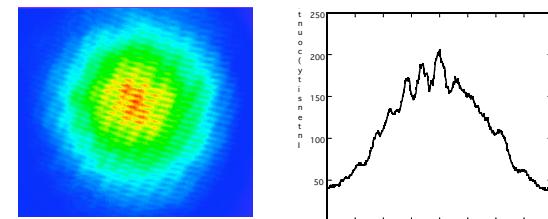
# Amplification Property of Pre-amplifiers



Far-field (upper) and  
Near-field (lower) pattern



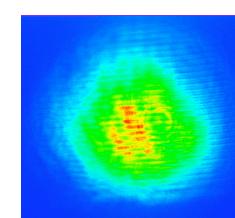
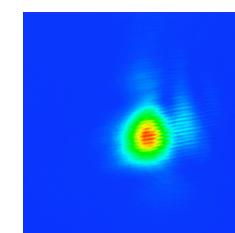
4-mm rod



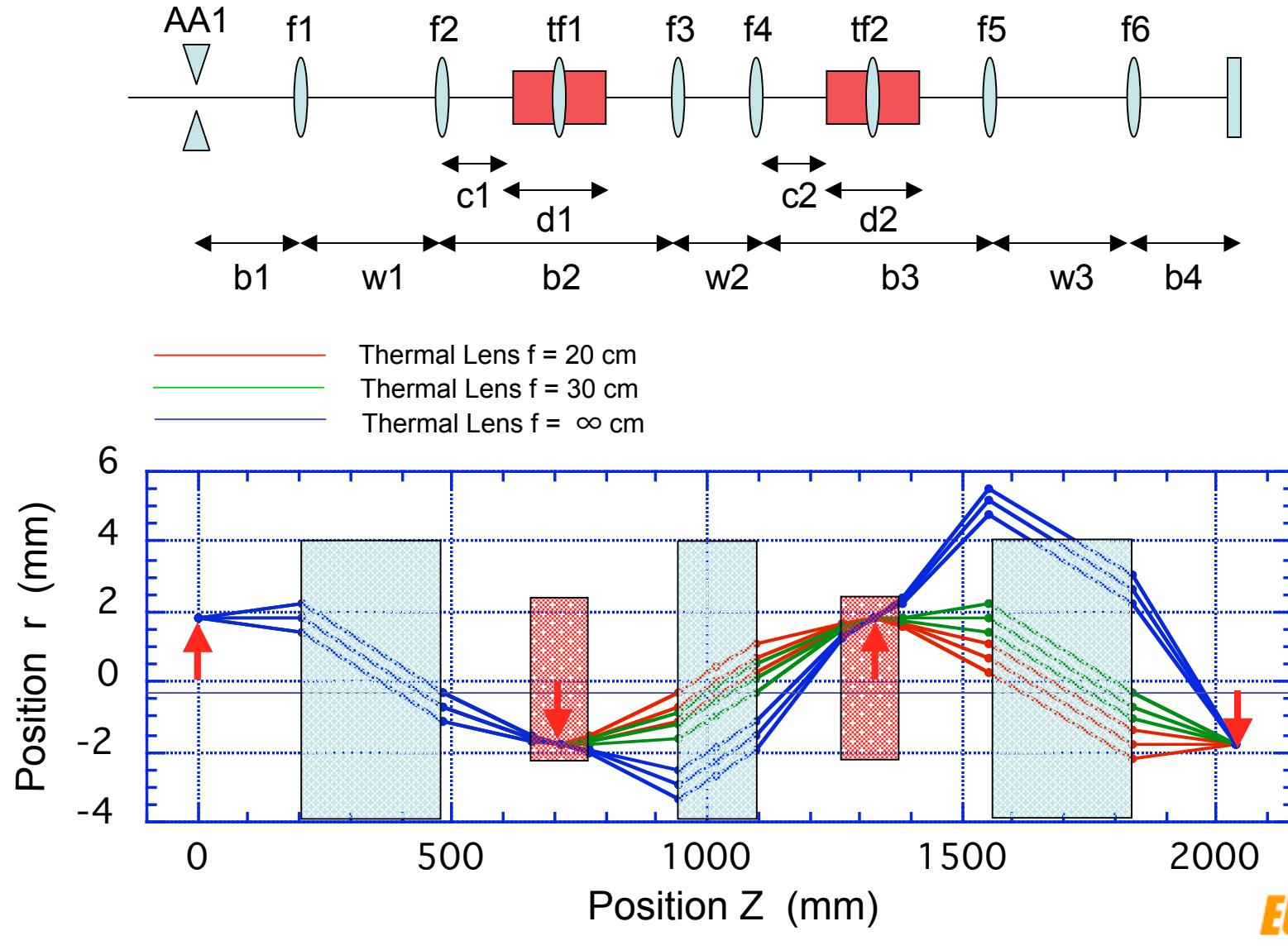
6-mm rod

Input pulse: 10 ns, 5 kHz | 300ps, 5kHz  
Output power: ~ 170 W | ~ 80W

Thermal lens: 200 - 1200 mm  
compensated by image relaying optics



# Image Relay and Thermal Lens Compensation

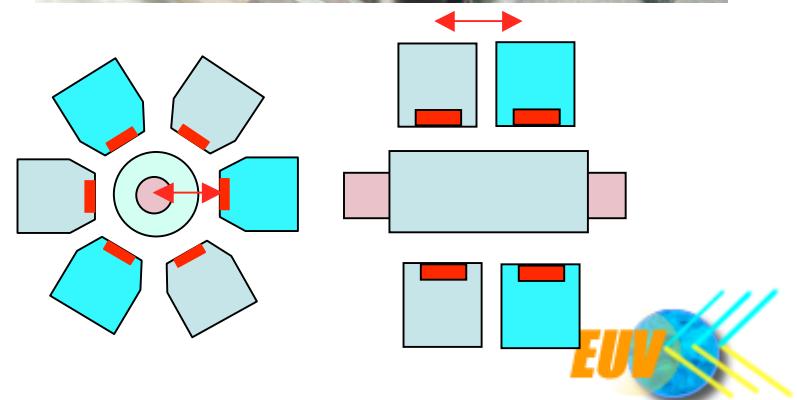
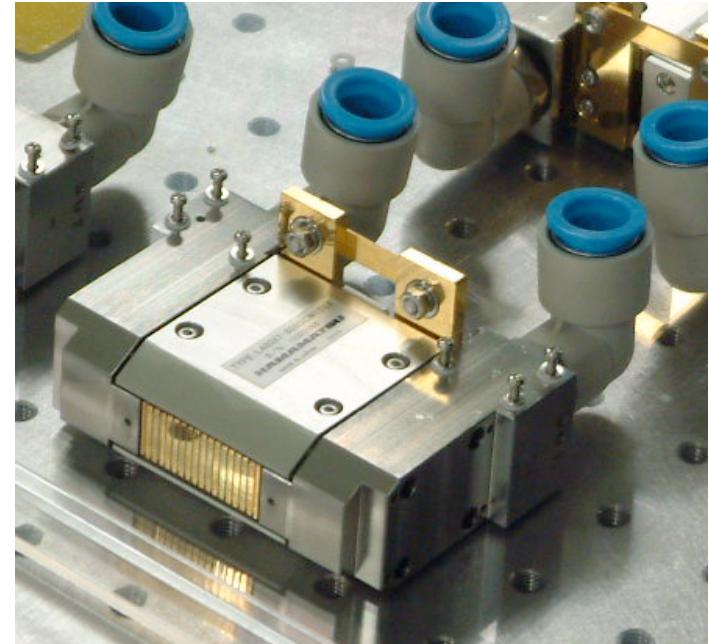
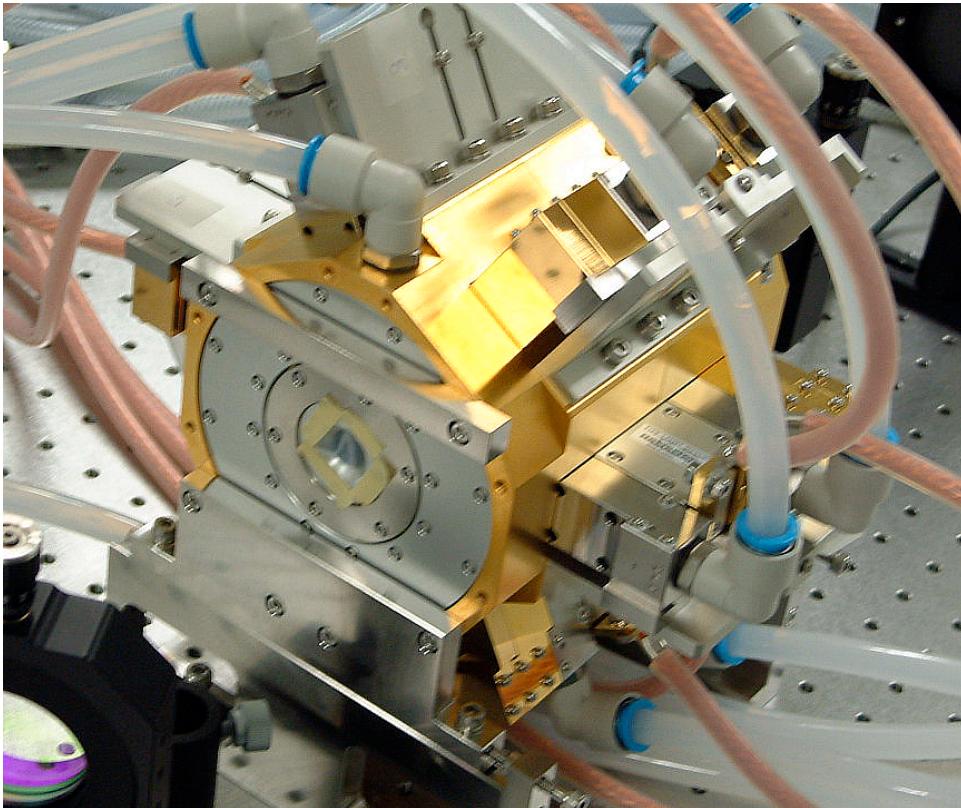


# Test Amplifier Module

Nd: YAG pumped by Pulse LD

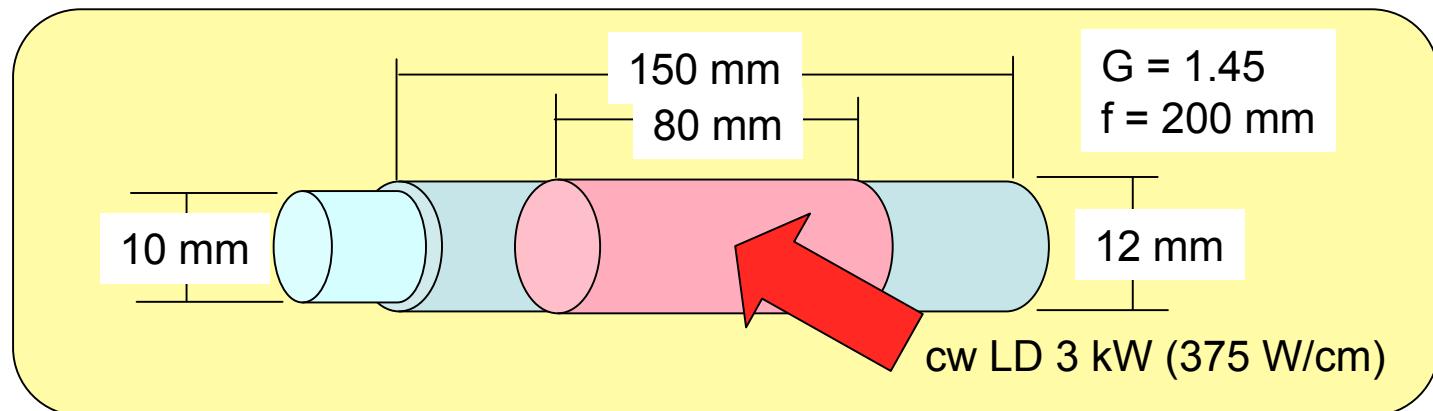
Rod: 10 -13 mm□, 150 mmL

LD: 6 x 750 W, 200 □s, < 2.5 kHz

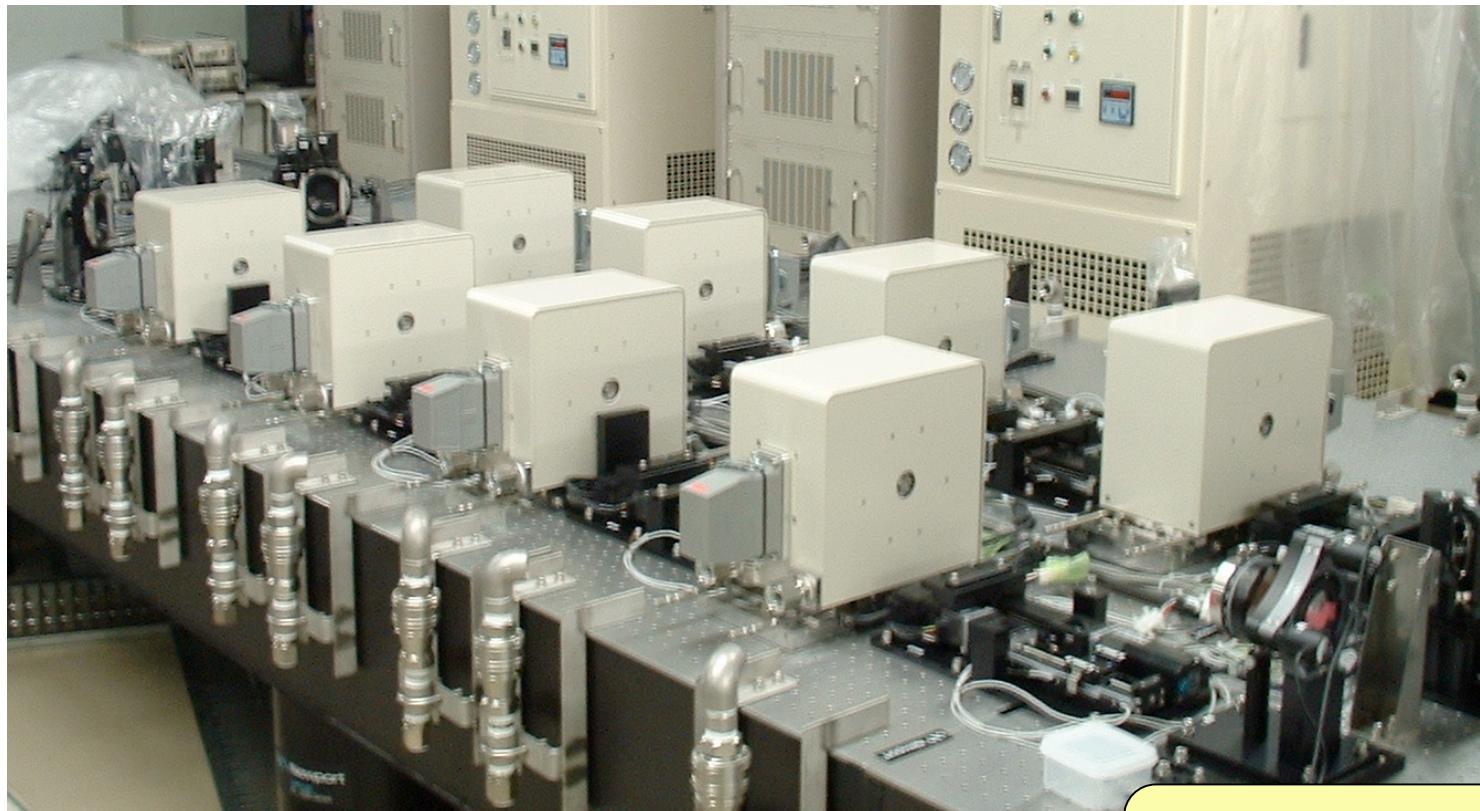


# Summary (Test Amplifier Module)

- / Uniform pumping was achieved by adjusting several parameters.
- / Diameter of 12 mm was selected
  - Gain :  $\times 1.45$  (at 3.0 kW Pumping)
  - Thermal lens : 20 cm (at 3.0 kW Pumping)
- / Thermal fracture of ceramic YAG rods increased up to 520 W/cm.
- / System analysis suggests that we need 8 amplifier modules pumped at 24 kW to get output power of 5 kW.



# Main Amplifier Chain of High Average Power Nd:YAG Laser



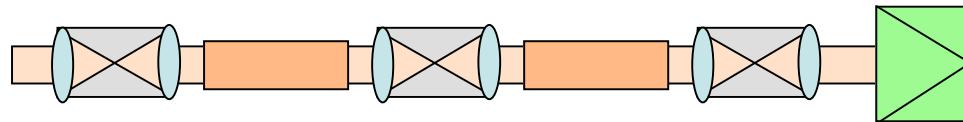
March, 2005

**1 J, 3 ns, 5 kHz  
5 kW Laser**

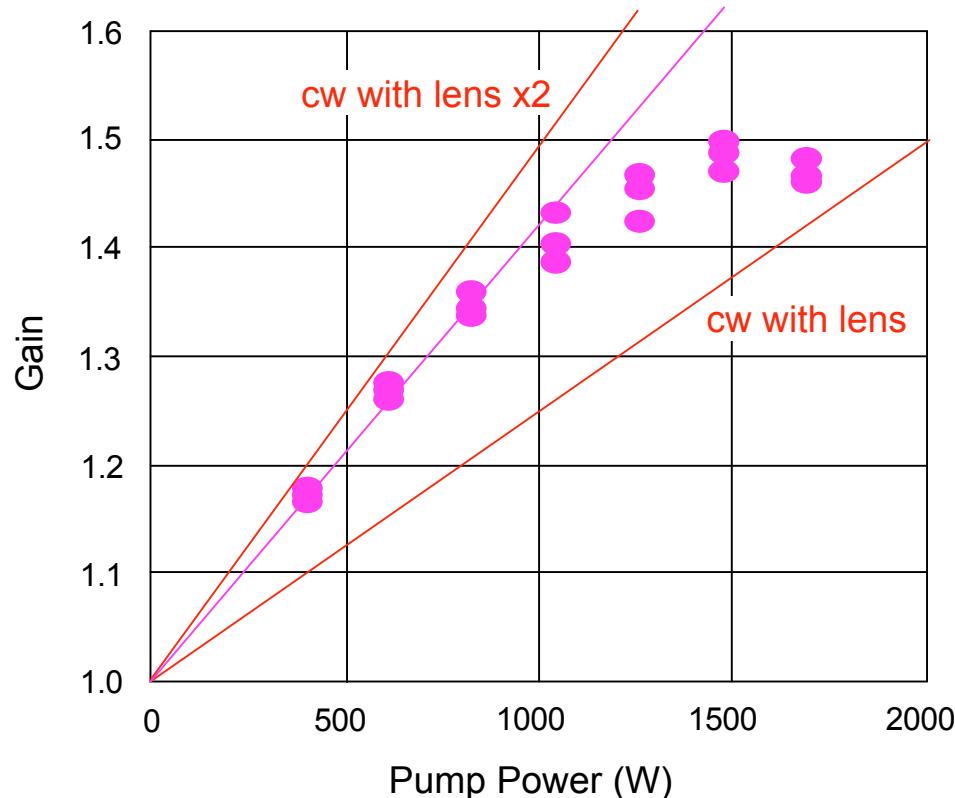


## 2 Unit Gain Property (12 mm[], 0.6 at %, with Lens)

From Front-End: a few W, 10 ns, 5 kHz

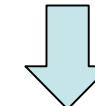


Thermal lens effect is compensated  
by adjusting distance of spatial filters.



Gain Saturation ??

We checked fluorescence spectrum.  
Center wavelength sifts according  
to pump power.

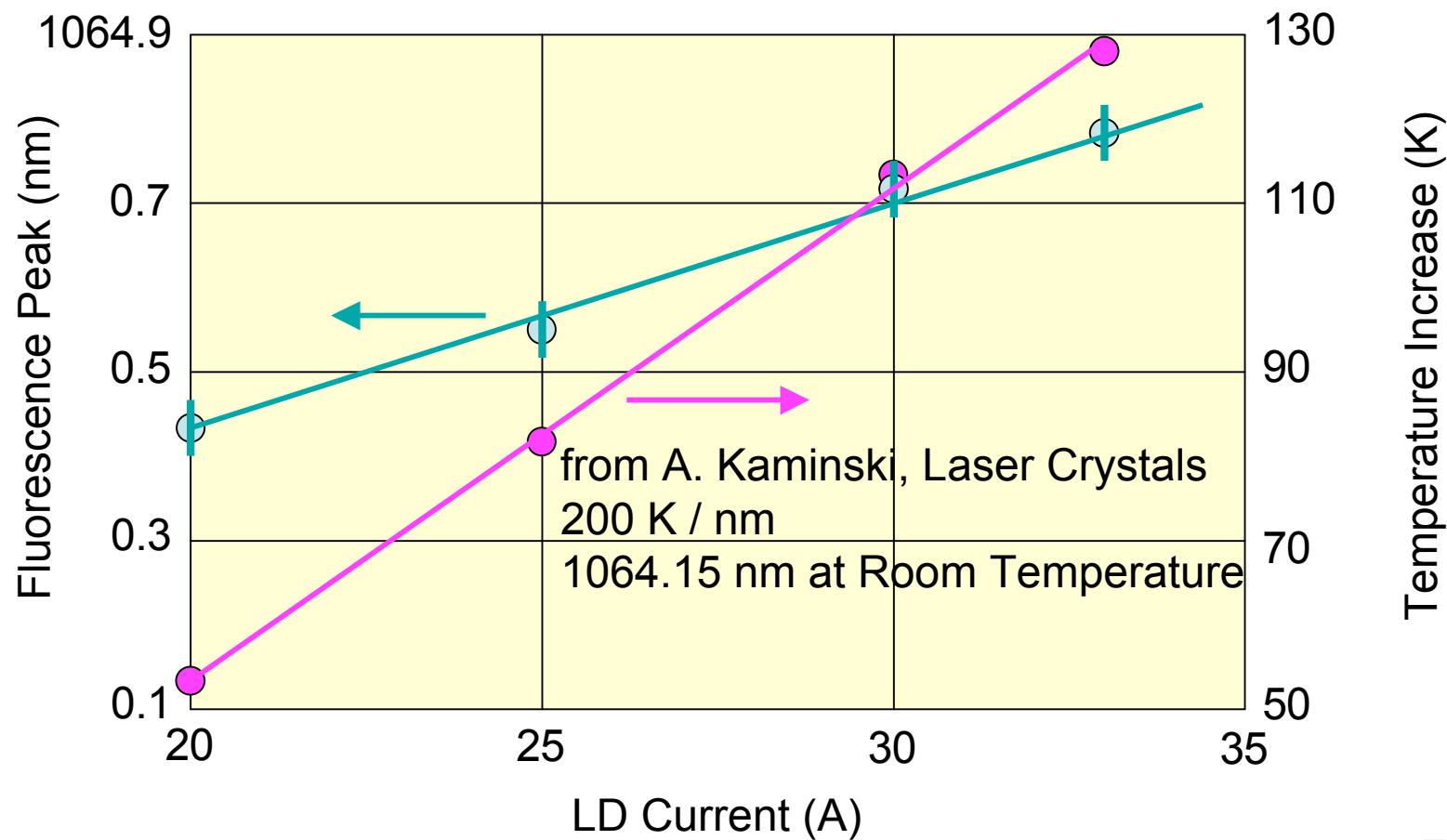


Improvement of cooling system  
for Nd:YAG rods



# Fluorescence Shift vs Pumping power

Unit 8, 10  $\square$ , 0.8 at%, 805 nm



## Wavelength Matching between Osc. and Main Amp.

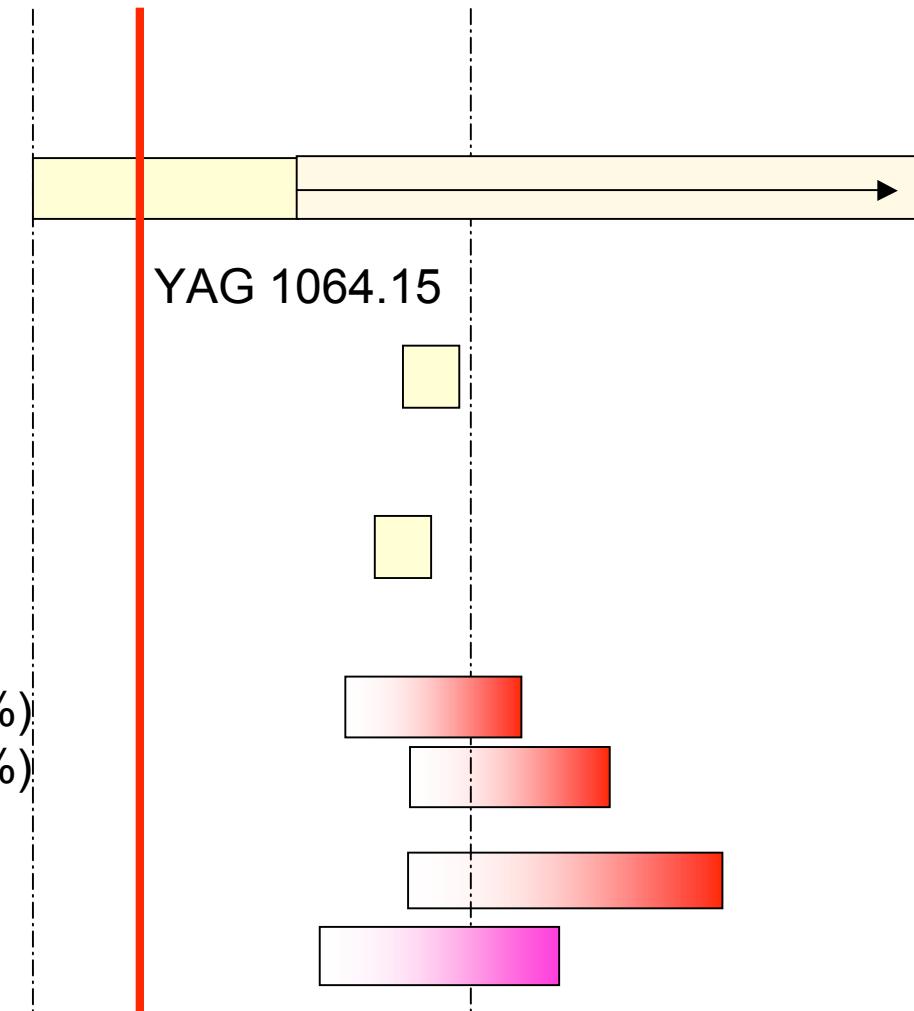
Fiber Osc.      1064.00 - .30  
                  1064.00 - 1065.00

Regen.            1064.42 , .48

4 mm Rod        1064.42

6 mm Rod        1064.35 -.54 (0.6 at%)  
                  1064.42 -.66 (0.8 at%)

Main Amp          1064.42 - .79  
                  1064.30 - .60



1064

1064.5

1065



# Optical Arrangement of 2 pass(4 Units) + 1 pass (4 Units)

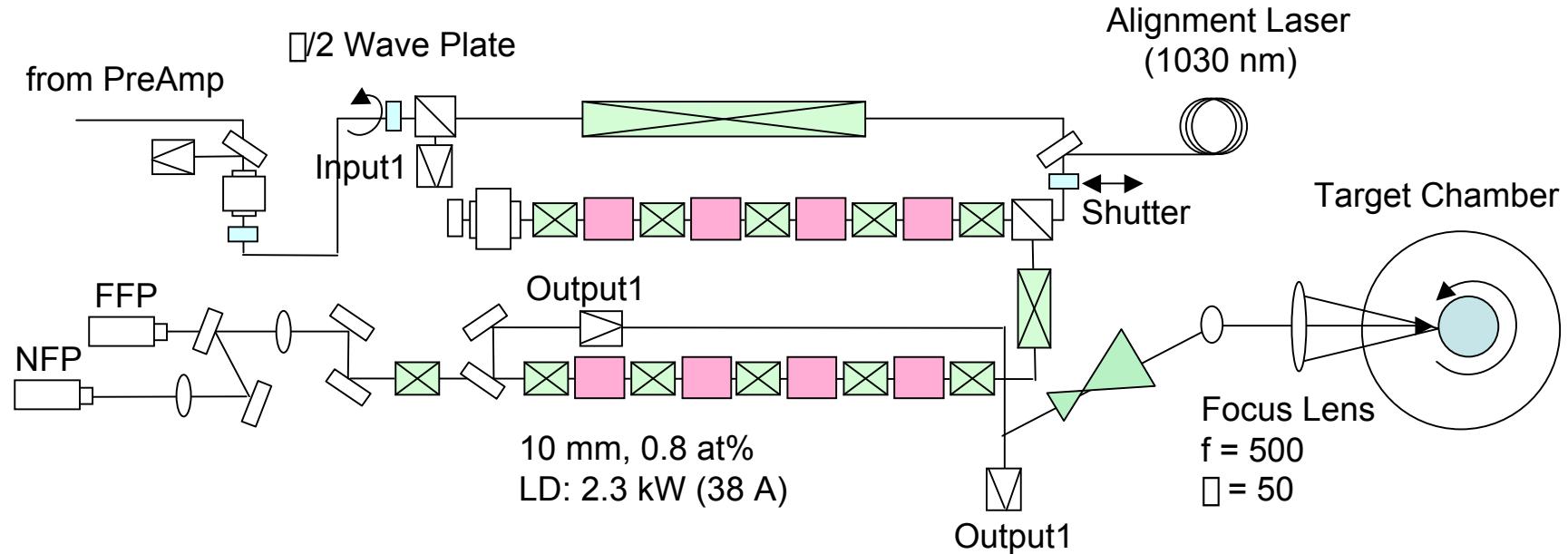
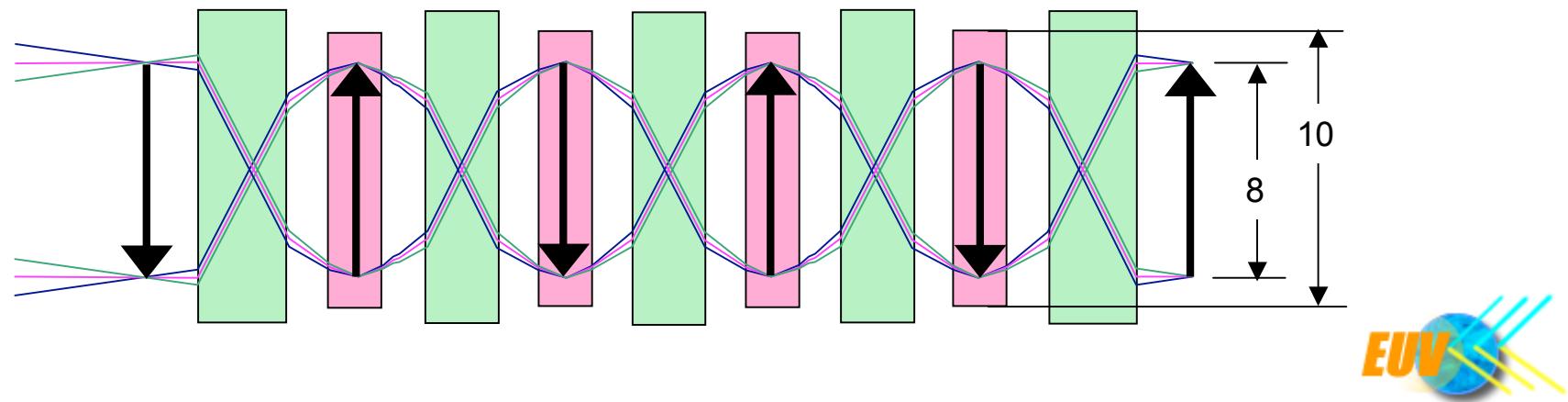
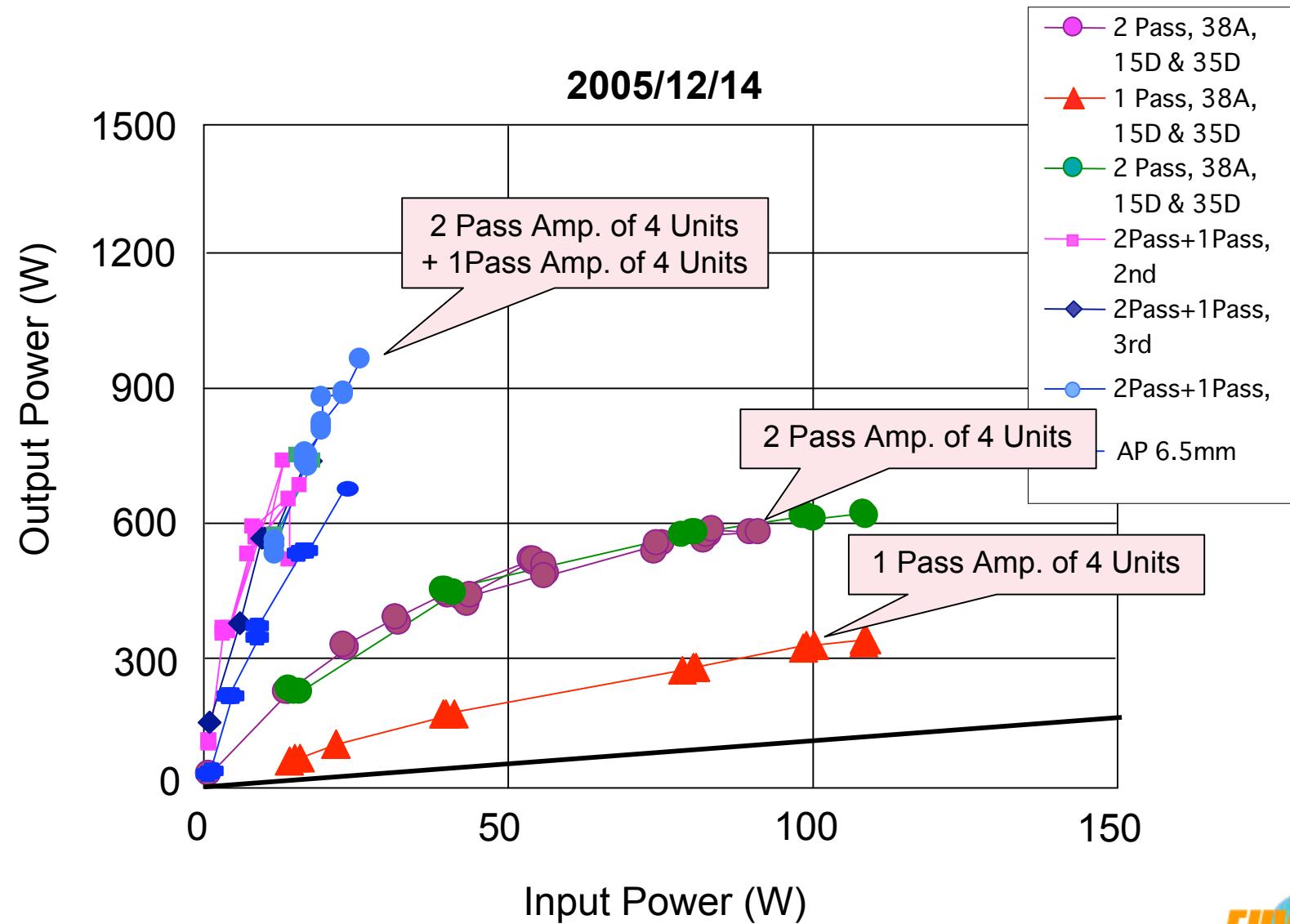


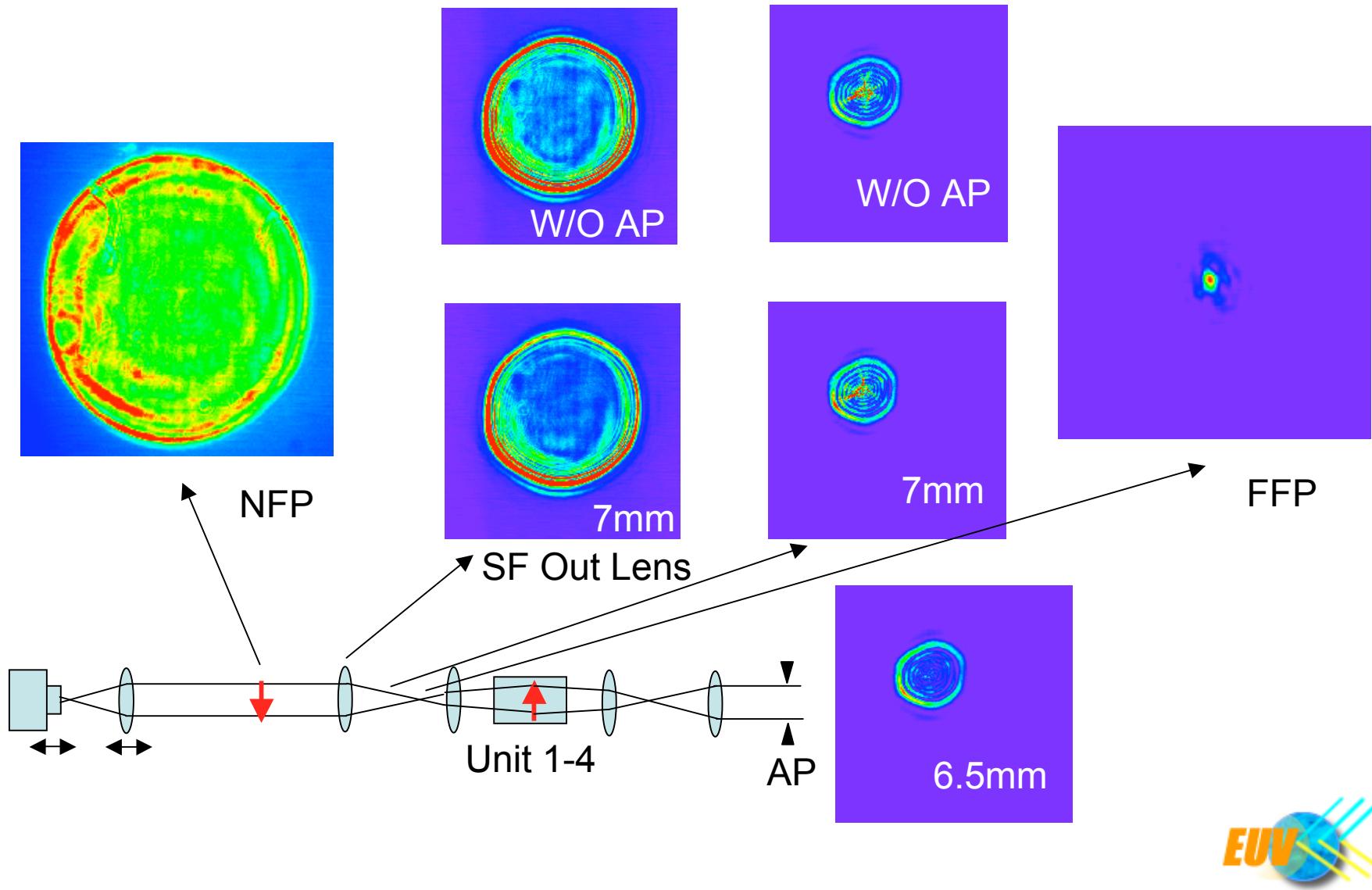
Image Relay and Compensation of Thermal Lens



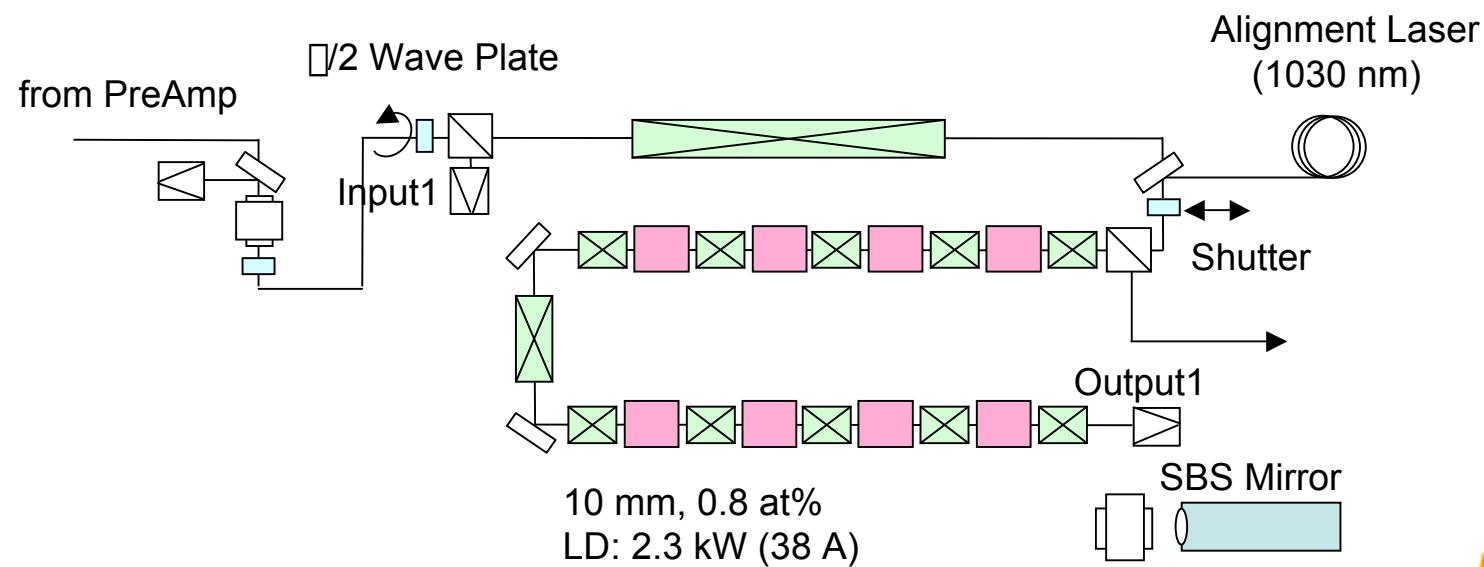
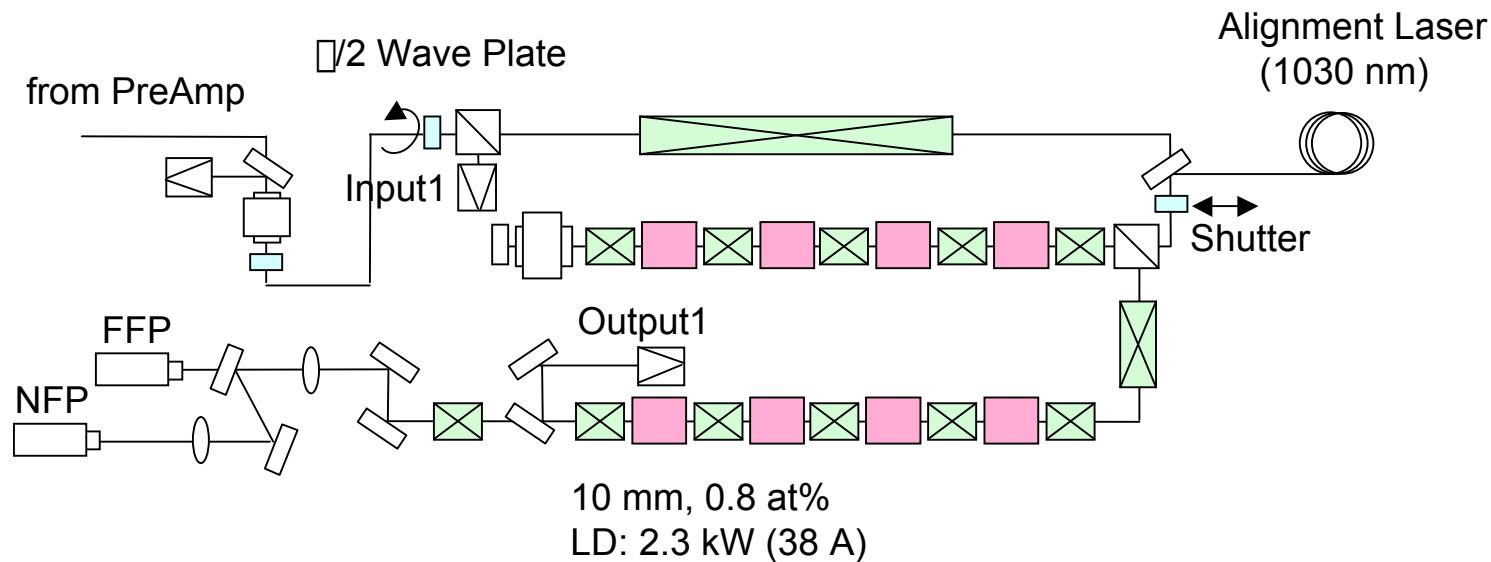
# Amplification Results of (4 Unit 2 Pass + 4 Unit 1 Pass)



# Beam Pattern Measurements

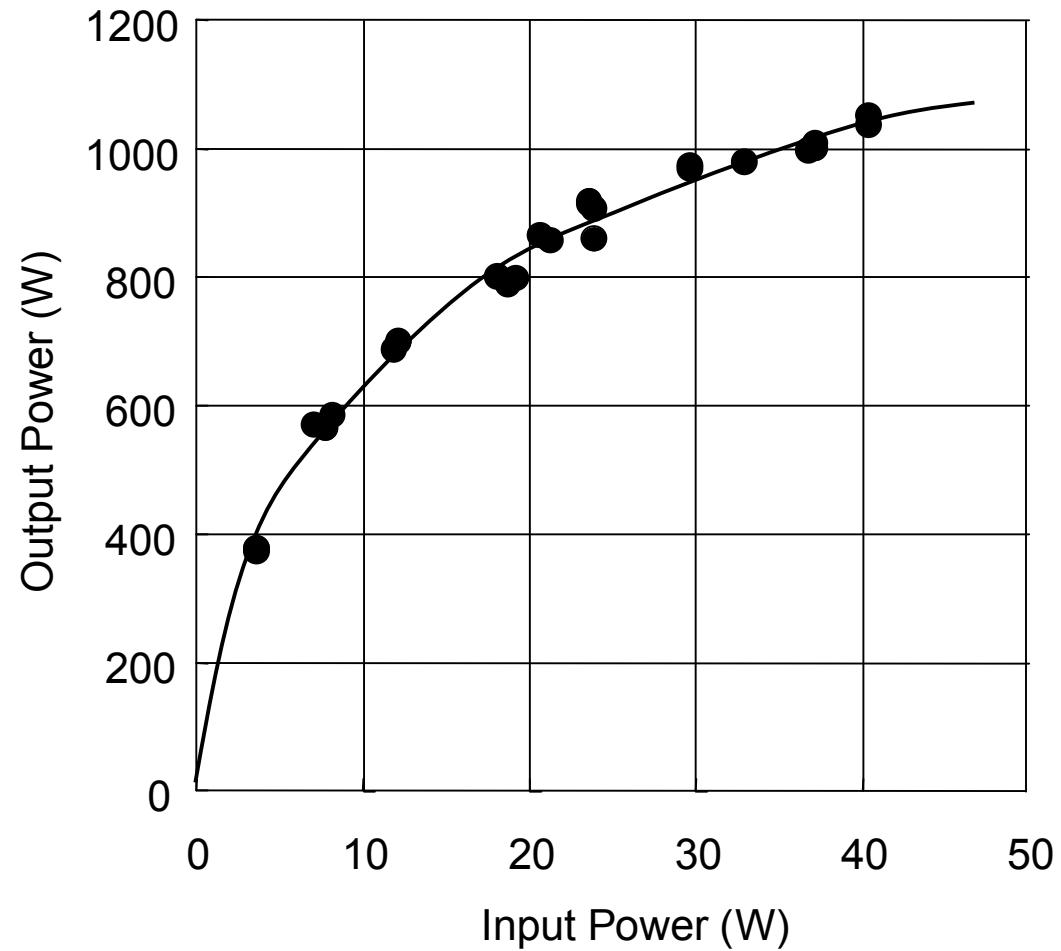


# Installation of SBS PC Mirror



## Amplification Results of (1 pass Amp. of 8 Units)

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# Summary

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## Front-end

- / Stable Single Longitudinal Oscillation      40 mW, Band Width of 100 kHz
- / Switch out by Fast EO Modulator      1.0 - 10.0 ns ([Arbitrary Pulse Shape](#))
- / Fiber Amplifier      740 nJ/3 ns → [1 mJ/3ns](#)

## Pre-Amplifier

- / Expected output power was almost obtained.      160 W → [200 W](#)
- / Our concept for compensation of thermal effects was checked.  
Further studies are required (ex. Wavefront collection by DM)

## Test Amplifier Module

- / Uniform pumping was achieved by adjusting several parameters.
- / Diameter of 10-12 mm was selected.       $G = 1.45$  , Thermal lens = 20 cm (at 3.0 kW)
- / System analysis suggests that we need 8 amplifier modules pumped at 24 kW  
to achieve output power of 5 kW.

## Main Amplifier Chain

- / All components were installed by the end of Mar. 2005.
- / Output of 1 kW was obtained by 1 pass amplification of 8 Units (at 2.5 kW).
- / Further studies (2 pass amplification, SBS PC Mirror)

